IRRIGATION'S ROLE IN ENHANCING WATER USE EFFICIENCY

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ABSTRACT

Irrigated agriculture is a vital component of total agriculture and supplies many of the fruits, vegetables, and cereal foods consumed by humans; the grains fed to animals that are used as human food; and the feed to sustain animals for work in many parts of the world. World-wide irrigation was practiced on about 263 million ha in 1996 with about 49% of the world's irrigation in India, China, and the United States. The objectives of this paper are to review irrigation worldwide in meeting our growing needs for food production, irrigation trends in the U.S., to discuss various concepts that define water use efficiency (WUE) in irrigated agriculture from both an engineering and agronomic view points, and to discuss the impacts of enhanced WUE on water conservation. Frequent reports indicate that scarcely one-third of our rainfall, surface water, or groundwater is used to produce plants useful to mankind. Without appropriate management, irrigated agriculture can be detrimental to the environment and can endanger sustainability. Irrigated agriculture is facing growing competition for low-cost, high-quality water. WUE in irrigated agriculture is broader in scope than most agronomic applications and must be considered on a watershed, basin, irrigation district, or catchment scale. The main pathways for enhancing WUE in irrigated agriculture are to increase the output per unit of water (engineering and agronomic management aspects), reduce losses of water to unusable sinks and reduce water degradation (environmental aspects), and reallocating water to higher priority uses (societal aspects).

KEYWORDS: Irrigation diversion, Efficiency, Basin, Salinity, Environment, Watershed

IRRIGATION AND THE WORLD'S NEED FOR FOOD, FIBER, AND WATER

Irrigation is vitally important in meeting the food and fiber needs for a rapidly expanding world population that reached six billion on October 12, 1999 and is currently increasing by about 80 to 85 million people each year. The United Nations projects that the world population in 2050 could be anywhere from 7.3 to 10.7 billion, assuming human reproductive fertility declines considerably in the future. If the world's population continues to increase at its present rate, in 2050 it will be 14.4 billion. Much of this growth will occur in the developing world. The African growth rate, if maintained, will lead to a doubling of its population in less than 25 years. While most demographers expect human reproductive fertility rates to decline further, the population in south-central Asia is currently projected to double in just 30 years, and Central America's population could double in only 35 years. The income of much of the increased population and its consumption of goods and services has also increased, adding to even more pressure on natural resources (soil and water) and energy supplies. While this income provides adequate nutrition for many people in other countries and regions, significant and even worsening malnutrition problems exist in other countries and regions.

WATER USE EFFICIENCY

Sinclair et al. (1984) described WUE on various scales from the leaf to the field. In its simplest terms, it is characterized as crop yield per unit water use. In its simplest terms, it is characterized as crop yield per unit water use. At a more biological level, it is the carbohydrate formed from

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CO_2, sunlight, and water through photosynthesis per unit transpiration. Brown (1999) has proposed that the upcoming benchmark for expressing yield may be the water required to produce a unit of crop yield, which is simply the long used "transpiration ratio" or the inverse of WUE. Often, the term WUE becomes confounded when used in irrigated agriculture. Bos (1980 and 1985) recommended that WUE with irrigation be based on the yield produced above the rainfed or dryland yield divided by the "net" evpotranspiration difference for the irrigated crop, which he called the yield : ET ratio. He also proposed the irrigated difference from the dryland yield divided by the "gross" applied water, which he called the yield : water supply ratio that is called irrigation WUE (I_{WUE}) here. These definitions are attractive, but difficult to apply, since many management factors could affect yield or could differ substantially between irrigated and dryland agriculture (or even rainfed practices), such as fertility, variety, pest management, sowing date, soil water content at planting, planting density, and row spacing. Defining WUE for irrigation is additionally complex because the scale of importance for the water resource shifts to the broader hydrologic basin, watershed, irrigation district, or irrigation project scale and the water components may not be so precisely defined and may become even more qualitative when such terms as "reasonable," "beneficial," or "recoverable" are employed (Burt et al., 1997). The objectives of this paper are to review irrigation worldwide in meeting our growing needs for food production, irrigation trends in the U.S., to discuss various concepts that define WUE in irrigated agriculture from both an engineering and agronomic view points, and to discuss the impacts of enhanced WUE on water conservation. It should be accepted that irrigation, by its purpose, should be the most effective means to improve WUE through increasing crop yield especially in semi-arid and arid environments. Even in sub-humid and humid environments, irrigation is particularly effective in overcoming short-duration droughts. However, irrigation, by itself, may not always produce the highest WUE possible. Readers are also referred to important review articles on irrigated agriculture like Clothier (1983), Clothier and Green (1994) and Pereira et al. (1996). Although much has changed around the world, as well as with irrigation water management and irrigation technology, in the past twenty years, Dr. Marvin Jensen's comment, "The greatest challenge for agriculture is to develop the technology for improving water use efficiency," (Karasov, 1982) remains true today in 2000.

WORLD POPULATION AND IRRIGATION TRENDS

The world's population and irrigated land area changes (Table 1) demonstrate that the per capita irrigated land has been constant at about 0.045 ha/person since the 1960s. Arable land [1,379 Mha in 1999 (FAOSTAT, 1999)] per capita has decreased from 0.38 ha/person in 1970 to 0.28 ha/person in 1990 (data not shown). Worldwide irrigated land was about 263 Mha (FAOSTAT, 1999) in 1996 (Table 1). Approximately 15 percent of the cultivated land in the world is irrigated and produces about 36 percent of the world's food (FAO, 1988). About two-thirds of the world's irrigation is in Asia (Table 2). Nearly 70 percent of the grain in China is harvested from irrigated lands; in India it is almost 50 percent (Brown, 1999). The FAO (1988) estimated that almost two-thirds of the increase in crop production needed in developing countries in the upcoming decades must come from yield increases, one-fifth from increased arable lands, and the remaining one-eighth from increased cropping intensity. They attribute almost two-thirds of the increase in arable land to come from an increase in irrigated land. Rhoades (1997) concluded that the required food production from developing countries must come primarily from irrigated land.

Table 2 shows worldwide irrigation by continent and the changes from1974 to1989. Although Asia has a high percent of the world's irrigation, its percent change was nearly equal to the change worldwide and per capita irrigated land (0.045 to 0.048 ha/person). Seckler et al. (1998) attempted to project global water demands. They concluded that around one-half of the increase in demand for water by the year 2025 could be met by increasing the effectiveness of irrigation.

Table 1. World population and irrigated land [sources: Rhoades, 1997; Ghassemi et al., 1995; Worldwatch Institute, 1999; FAO web data (FAOSTAT, 1999)].

Year	Population	Irrigated Area	Per capita irrigated area
	billions	Mha	ha per person
1800	1	8	0.008
1900	1.5	40	0.027
1950	2.5	94	0.038
1961	3.07	139	0.045
1965	3.35	151	0.045
1970	3.71	169	0.046
1975	4.08	190	0.047
1979	4.37	209	0.048
1980	4.45	211	0.047
1985	4.86	226	0.046
1990	5.30	239	0.045
1994	5.63	249	0.044
1996	5.75	263	0.046

While the remaining water needs could be met by small dams and conjunctive use of aquifers, medium sized dams will certainly be needed. Postel (1993) noted the slow worldwide irrigation expansion since the 1970s, barely averaging 1 percent, and she attributed this to declining international lending and the long lead time required to develop and complete new projects. In addition, the costs for irrigation projects have escalated, making such investments more difficult to justify. Table 1 illustrates this fact rather well as the rate of change in irrigated land exceeded the worldwide population growth rate until around 1980. Also, environmental concerns caused by irrigation raise serious questions and pose difficult problems in many parts of the world (Rhoades, 1997), especially with regards to irrigation sustainability. Rhoades (1977) quoted Ghassemi et al. (1995) and others who estimated around 40 to 50 Mha of irrigated lands may be already degraded by waterlogging, salination, and sodication.

IRRIGATION TRENDS IN THE UNITED STATES

Gardner et al. (1996) and Vaux et al. (1996) provided current reviews of U.S. irrigation. The irrigated area in the U.S. since 1969 is now rather stable at around 20 Mha (Fig. 1). The critically important fact is the decline in annual applications from 650 mm of applied water in the early 1970s to about 500 mm in recent years. This represents perhaps both improved and careful

Table 2. Irrigated area by continent. (adapted from Gleick, 1993)

Continent	1974	1979	1984	1989	Change in irrigated area (1974 - 1989)	1989 per capita irrigated area
	Mha				percent	ha per person
World	185.2	209.2	221.0	232.8	25.7	0.045
Africa	9.3	9.8	10.6	11.2	19.6	0.018
North and Central America	22.6	27.6	25.4	25.9	14.7	0.061
South America	6.3	7.2	8.0	8.8	39.3	0.030
Asia	119.1	131.6	140.1	146.4	23.0	0.048
Europe	12.6	14.4	15.6	17.2	37.1	0.035
Oceania	1.6	1.7	1.9	2.1	24.5	0.083
USSR	13.7	17.0	19.5	21.1	54.0	0.074

management and improved irrigation systems. Jensen et al. (1990) gave a more thorough discussion of global irrigation advances and regional breakdown of the U.S. irrigation development. Many factors are involved in irrigation expansion or decline in the U.S. including the global problem related to waterlogging and salination and other water quality degradation issues (Rhoades, 1997; Jensen et al., 1990).

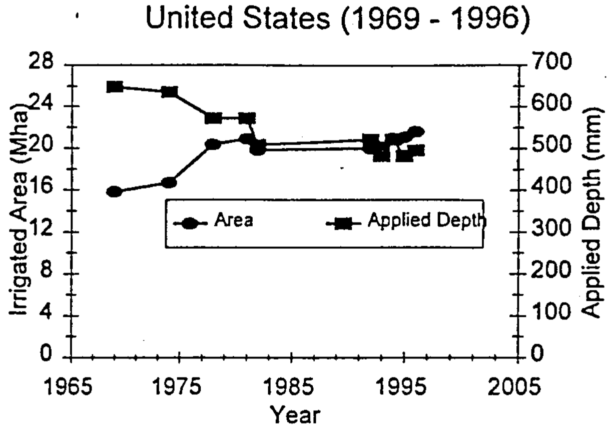

Figure 1. The irrigated area trend in the U.S. since 1969 (ERS, 1997).

Figure 2 shows the USDC (1999) irrigated land changes since the 1992 agricultural census indicating a net increase of 2.28 Mha. Interestingly, several "pockets" of irrigated expansion have occurred along the Mississippi Delta region from northeast Louisiana to southern Missouri; in the western Texas High Plains; across eastern Nebraska; in the San Luis Valley in south Central Colorado; and throughout the Central Valley of California. The northwest U.S. and the inter-mountain West also showed widespread expansion too, although not as concentrated. This net expansion is rather significant, representing almost 10 percent of the irrigated land in the U.S.

Areas of irrigation decline also seemed "clustered," but in different areas such as south Florida; southwest Georgia; the rice (*Oryza sativa* L.) belt in Texas and Louisiana; and the Texas lower Rio Grande Valley; Hawaii; and the central plains regions from the northeastern Texas Panhandle, Oklahoma Panhandle, Southwest Kansas, and parts of Colorado. Although the 1997 agricultural census (USDC, 1999) doesn't specify the commodity area changes as to irrigated and nonirrigated crops, it is apparent that in the Mississippi Delta rice and soybean [*Glycine max* (L.) Merr] increased and cotton (*Gossypium hirsutum* L.) decreased, while cotton and peanut (*Arachis hypogaea* L.) in the Texas southwestern High Plains (Dawson and Gaines counties) increased, and irrigated corn (*Zea mays* L.) increased in both the northwestern Texas Panhandle (Dallam county) and Nebraska, where soybean also increased. Irrigated potato (*Solanum tuberosum* L.) production has likely increased substantially during this period in the San Luis Valley of

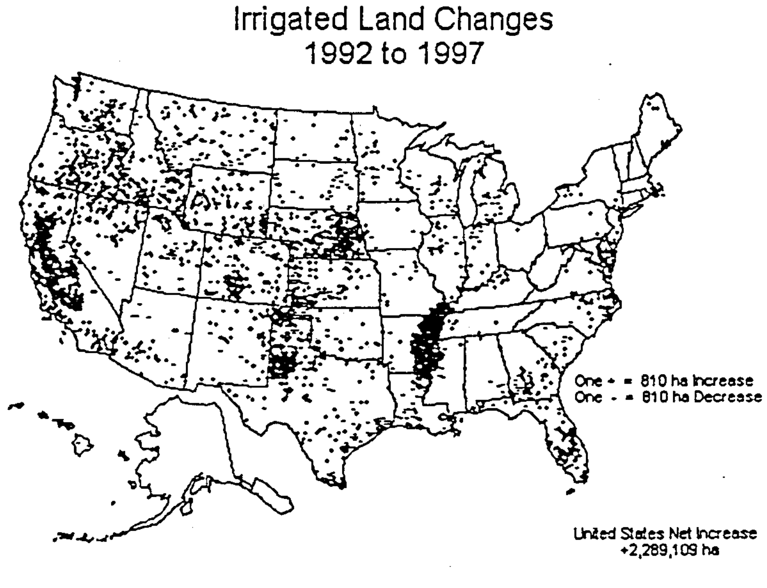

Figure 2. The U.S. irrigated land changes since the 1992 agricultural census indicating a net increase of 2.89 Mha (USDC, 1999). Illustration supplied by the USDA-NASS, Washington, D.C.

Colorado and across the Northwest (Idaho, Washington, and Oregon). Although cotton declined in Mississippi, it increased across the southeastern U.S. (Georgia and the Carolinas) due to improved boll weevil (*Anthonomus grandis grandis*) control now available through eradication programs. The majority of the increases in grain sorghum (*Sorghum bicolor* L. Moench) were in southwestern Kansas and were likely irrigated. Irrigated grain production remains important for the continued increase in cattle feeding in Texas, western Kansas, Nebraska, and northeast Colorado. Dairy migrations in the 1992-1997 period have occurred to the Central Valley in California from southern California and to eastern New Mexico along with south-central Idaho.

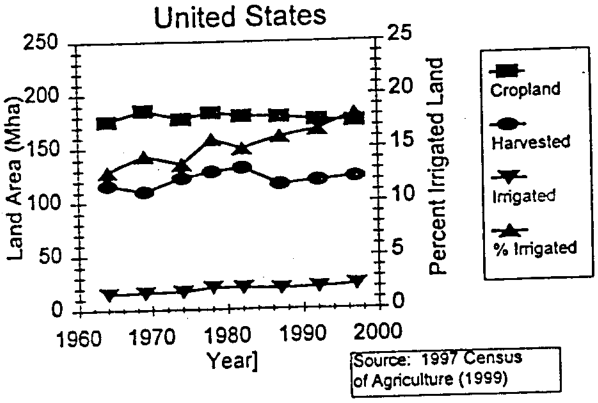

Figure 3. The U.S. planted cropland, the irrigated cropland, and the percent of the cropland that was irrigated since 1964 (USDC, 1999).

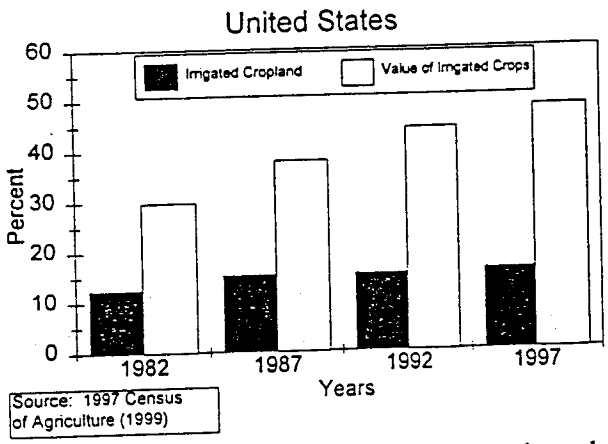

Figure 4. The U.S. planted cropland, the irrigated cropland, and the percent of the cropland that was irrigated since 1964 (USDC, 1999).

Figure 3 shows the U.S. total harvested and irrigated cropland and the percent of the cropland that was has been irrigated since 1964 (USDC, 1999). During the period 1964-1997, total cropland declined slightly (from about 185 Mha to about 175 Mha) while harvested cropland was more variable and increased from 116 Mha to 122 Mha.

Irrigated land area increased from 15 Mha to 22 Mha during this period (USDC, 1999). The percentage of U.S. cropland that is irrigated continually increased from almost 13 percent in 1964 to more than 18 percent in 1997 (USDC, 1999) (interestingly, this percentage is almost exactly the same as the world value). Remarkably, this small fraction of U.S. farm land produced almost 50 percent of the total value of crops in 1997 (USDC, 1999) (Fig. 4). Table 3 presents a selected summary of the major irrigated crops in the U.S. The high percentage of irrigation used in orchards, vegetables, potatoes, even hay [especially alfalfa (*Medicago sativa* L.)], and cotton lead to the importance of irrigation to U.S. agricultural production.

Table. 3. Percentage of selected crops produced with irrigation in 1992 (ERS, 1997).

Crop	Irrigated Production	Irrigated Area
	percent	Mha
Rice	100	1.3
Orchards	76	---
Potato (Irish)	71	0.4
Vegetables	65	1.0
Cotton	34	1.5
Corn (grain)	14	3.9
All hay	15	3.5
Wheat	7	1.7

The types of irrigation systems used have dramatically changed through the years. Surface (various gravity methods) irrigation decreased from 63 percent in 1979 to about 50 percent in 1994 (ERS, 1997) while low-pressure systems (drip, trickle, microsprays, etc.) increased from about 0.6 percent in 1979 to almost 4 percent in 1994. One of the larger and more obvious changes was to center pivot sprinklers. Although subirrigation accounts for a rather insignificant amount, it is important in areas where subsurface drainage involving watertable control technology is used to improve crop performance as well as water quality. The percentage change in these major categories during the 1979 to 1994 period were -20% for surface, 17% for sprinkler, 70% for center pivot, 445% for microirrigation, and 49% for subirrigation. Of course, the rather large percentage increase in drip systems (and other low pressure systems) stems from their small quantity.

WUE IN IRRIGATED AGRICULTURE

These irrigation statistics demonstrate unquestionably the important role that irrigated agriculture has not only in the U.S. but worldwide, and the need to enhance WUE in irrigated agriculture. Although the crop species and even the genotype together with available energy from sunlight are vitally important to WUE (primarily through the CO_2 pathway), water often is the critically important element in agriculture. Water is important in rainfed agriculture, critically important in semiarid dryland agriculture, and explicitly important in irrigated agriculture. Wallace and Batchelor (1997) offered four options for enhancing WUE in irrigated agriculture (Table 4), and they point out that focusing on only one category will likely be unsuccessful.

Table 4. Examples of options available for improving irrigation efficiency at a field level adapted from Wallace and Batchelor (1997).

Improvement Category	Options
Agronomic	crop management to enhance precipitation capture or that reduces water evaporation (crop residues, conservation till, plant spacing, etc.) ; improved varieties; advanced cropping strategies that maximize cropped area during periods of lower water demands and/or periods when rainfall may have greater likelihood of occurrence
Engineering	irrigation systems that reduce application losses and/or improve distribution uniformity; cropping systems that can enhance rainfall capture (crop residues, deep chiseling or paratilling, furrow diking, dammer-diker pitting, etc.)
Management	demand-based irrigation scheduling; slight to moderate deficit irrigation to promote deeper soil water extraction; avoiding root zone salinity yield thresholds; preventive equipment maintenance to reduce unexpected equipment failures
Institutional	user participation in an irrigation district (or scheme) operation and maintenance; water pricing and legal incentives to reduce water use and penalties for inefficient use; training and educational opportunities for learning newer, advanced techniques

WUE is generally defined (Viets, 1962) as

$$\mathrm{WUE} = \frac{\text{Crop yield (usually the economic yield)}}{\text{Water used to produce the yield}} \quad [1]$$

If the crop yield is expressed in g m^{-2} and the water use is expressed in mm, then WUE has units of kg m^{-3} on a unit water volume basis or g kg^{-1} when expressed on a unit water mass basis. WUE (Sinclair et al., 1984) can also be computed on a dry matter basis, and often the economic yield may not be expressed on a "dry" basis but rather at some standard water content for the commodity. Although useful in many analyses, WUE doesn't discriminate what role irrigation had in the WUE. Bos (1980 and 1985) developed expressions that can, perhaps, more consistently discriminate the role that irrigation has in WUE. His expressions can be written for the ET water use efficiency (ET_{WUE}) and irrigation water use efficiency (I_{WUE}) as

$$ET_{WUE} = \frac{(Y_i - Y_d)}{(ET_i - ET_d)} \quad [2]$$

$$I_{WUE} = \frac{(Y_i - Y_d)}{I_i} \quad [3]$$

where Y_i is the yield and ET_i is the ET for irrigation level "i," Y_d is the yield and ET_d is the ET for an "equivalent" dryland or rainfed only plot, and I_i is the amount of irrigation applied for irrigation level "i." Of course in most arid areas, Y_d would be zero or small; however, ET_d could be much greater than zero and variable depending on the agronomic practices. In semiarid and rainfed areas, Y_d could be determined several ways. In the strictest sense, it would be the yield under exactly the same management as the "i" treatment or system, but without irrigation. In a more comparative system, it might be estimated by yields from "comparable" dryland/rainfed plots that were not irrigated. Often however, agronomic practices differ substantially between dryland and/or rainfed and irrigated practices (variety, sowing date, fertility management, pest management, sowing density, planting geometry, etc.). Thus, quite different results might be obtained for Y_d and ET_d based upon differences in management.

The water use in Eq. (1) is difficult to determine precisely. So, in some situations, a "benchmark" WUE (WUE_b) is used by many irrigation practitioners. It can be defined as

$$WUE_b = \frac{\text{Yield (usually the economic yield)}}{(P_e + I + SW)} \quad [4]$$

where P_e is "effective" rainfall, I is irrigation applied, and SW is soil water depletion from the root zone during the growing season. The denominator of Eq. (4) is a surrogate estimate for the water used to produce the crop depending on the neglect of percolation, ground water use, and surface runoff. Experienced practitioners can use Eq. (4) for a specific region and to identify differences among irrigation methods and/or irrigation management.

Howell et al. (1990) presented an expression for field WUE based on Cooper et al. (1987) and Gregory (1990) as

$$\mathrm{WUE} = \frac{(\mathrm{HI\ DM})}{\left\{T\,(1 - \mathrm{WC})\left[1 + \dfrac{E}{(P + I + SW - D - Q - E)}\right]\right\}} \qquad [5]$$

where HI is the harvest index (dry yield per unit dry matter), DM is dry matter in g m^{-2} (it has to be the same as the DM component used to calculate HI whether aboveground DM or total DM including roots), T is transpiration in mm, WC is the standard water content used to express the economic yield (in a fraction; i.e., 0.15 to 0.155 is common for corn and 0.14 for other cereals), E is soil water evaporation in mm, P is precipitation in mm, I is irrigation in mm, SW is soil water depletion from the root zone in mm, D is deep percolation below the root zone in mm, and Q is surface runoff in mm. In some cases, other water balance components, like interception or runon or upward flow from groundwater into the root zone, may need to be considered. Equations (1, 4, and 5) illustrate the common problems encountered in accurately assessing WUE from field measurements. Both P and I may contribute water to surface runoff, Q, making estimates of effective precipitation, P_e, difficult to determine in some cases. Likewise, both P and I may contribute or cause water to move past the crop root zone resulting in difficulties in characterizing D. Profile soil water depletion can be measured, but it typically can only be determined at a few discrete points in a plot or field. The stochastic distribution of P across a plot or field is often ignored together with the distribution of I, which is known to be more predictable, but still probabilistic. All of these spatial variations impact ET and soil water depletion, SW. To obtain reproducible and reliable estimates for P, I, Q, D, and SW to estimate ET in Eqs. 1 or 2, extreme measures like plot leveling and bordering may be required. These techniques, although widely used in arid and semi-arid experiments, may be impractical in many situations or induce undesired effects on ET_d or Y_d, particularly in higher rainfall regions, and even affect D in those cases both by changing the profile soil water balance and by leaching crop nutrients from the root zone affecting Y_i.

Equation (5) represents all of the agronomic and engineering mechanisms offered by Wallace and Batchelor (1997) to enhance WUE. These are 1) increasing the harvest index through crop breeding or management; 2) reducing the transpiration ratio (T/DM) by improved species selection, variety selection, or crop breeding; 3) maximizing the dry matter yield through enhanced fertility, disease and pest control, and optimum planting; and/or 4) increasing the transpiration (T) component relative to the other water balance components. In particular, element 4 might be obtained by reducing E by increasing residues, shallow mulch tillage, alternate furrow irrigation, or narrow row planting; reducing D by avoiding over filling the root zone and minimizing leaching to the absolute minimum for salinity control; and reducing Q by using furrow diking, dammer diking, crop residues, or avoiding soil compaction and hardpan problems while increasing soil water depletion from the profile by gradually imposing soil water deficits, deeper soil wetting, or using deeper rooted varieties. Although both elements 1 and 2 are biologically controlled and difficult to manipulate, some diversity and variability may exist in the field that can be controlled. Element 3 is the focus of much current precision agriculture research to enhance yields relative to needed inputs at the correct time and location in the field. Element 4 is the basis of almost all current water conservation technologies to enhance rainfall capture and to improve irrigation technologies to avoid or minimize application losses.

Engineers have long characterized irrigation performance using various "efficiency" and "uniformity" terms (Burt et al., 1997). Wang et al. (1996) offered a new efficiency term, called the "general" efficiency, E_g, based on the ratio of transpiration to the sum of the volume of applied water and the volume of the deficit expressed as

$$E_g = \frac{\alpha \; E_a E_s}{\left(E_a + E_s - E_a E_s\right)} \qquad [6]$$

where E_g is the "general" irrigation efficiency fraction, α is the transpiration fraction of ET (T/ET), E_a is the application efficiency fraction (volume of water stored in the root zone per unit water volume delivered to the field), and E_s is the storage efficiency fraction (volume of water stored in the root zone per unit water volume needed in the crop root zone). Equation (6) is related to Eq. (5) without the yield parameters that have become integral in WUE. It clearly emphasizes, like Wallace and Batchelor (1997), the need to maximize transpiration while minimizing application losses and meeting the crop water needs. Wang et al. (1996) believed that E_g would be more closely associated with crop yield than the individual "efficiency" terms since it could simultaneously consider both deep percolation losses and irrigation deficits while excluding the soil water evaporation loss that may not directly contribute to crop yield. Equation (6) can be applied to differing irrigation scales from plots to watersheds, although like all efficiency characterizations (Burt et al., 1997), the various water components concepts remain challenging to measure in the field.

Examples:

Table 5 presents WUE, ET_{WUE}, and I_{WUE} values for corn at Bushland, TX irrigated under several different irrigation application methods and water management treatments. Several items from these data are evident – 1) I_{WUE} is typically much greater than just WUE; 2) both WUE and I_{WUE} do not differ greatly among irrigation methods when operated to avoid and/or minimize application losses; 3) I_{WUE} generally tends to increase with a decline in irrigation if that water deficit does not occur at a single growth period [i.e., see the surface data with specific period deficits (likely attributed to enhancing the transpiration component in relation to total water use)]; 4) both WUE and I_{WUE} for corn at Bushland, TX, are maximized with a small

Table 5. Example WUE†, ET_{WUE}, and I_{WUE}†† values for corn irrigated by surface (level basins), LEPA (low energy, precision application) and drip/microirrigation (subsurface drip and surface drip) [Musick and Dusek, 1980; Howell et al., 1995; and Howell et al., 1997, respectively] at Bushland, TX. The data were averaged for two years.

Irrigation Method	Irrigation Fraction	WUE†	ET_{WUE}	I_{WUE}††
		kg m^{-3}	kg m^{-3}	kg m^{-3}
Surface (level basins) 1976 & 1977	Full	1.35	2.66	2.41
	Vegetative Deficit	1.23	3.01	2.53
	Pollination Deficit	0.91	1.97	1.98
	Grain-Filling Deficit	1.11	1.96	2.06
	0.00	0.00	----	-----
LEPA 1992 & 1993	1.00	1.35	2.13	1.73
	0.80	1.45	2.56	2.07
	0.60	1.38	2.59	2.01
	0.40	1.38	3.06	2.36
	0.20	1.28	3.85	2.10
	0.00	0.93	----	----
Subsurface Drip 1993 & 1994	1.00	1.42	1.98	1.79
	0.67	1.53	2.43	2.35
	0.33	1.21	2.37	2.28
	0.00	0.43	----	----
Surface Drip 1993 & 1994	1.00	1.39	1.95	1.78
	0.67	1.52	2.37	2.28
	0.33	1.23	2.42	2.35
	0.00	0.43	----	----

† Yields based on 15.5 percent grain water content.
†† Preplant irrigations were excluded.

water deficit (likely attributed to reducing unnecessary soil water evaporation while not reducing transpiration) while ET_{WUE}, generally, is highest with less irrigation implying full use of the applied water and perhaps a tendency to promote deeper soil water extraction to make better use of both the stored soil water and growing season rainfall. Tanner and Sinclair (1983) presented data that supported their concept of greater WUE of corn in more humid environments. Their mean WUE was 1.8 kg m^{-3} for several western sites while it averaged more than 2.5 kg m^{-3} in more humid sites. The WUE values for corn at Bushland, TX, are lower than values in Tanner and Sinclair (1983; their Table 5) reflecting the greater vapor pressure deficit and greater evaporative demand in the Southern High Plains for corn. However, this region has some of the nation's highest mean county corn yields (TASS, 1999; NASS, 1999). For example, Dallam County in Texas averaged 12.8 Mg ha^{-1} more than 61,100 ha in 1998, which was a drought year, (TASS, 1999) compared with the best county in Iowa in 1998, Scott County, which averaged 10.6 Mg ha^{-1} more than 47,100 ha (NASS, 1999). Interestingly, the higher Bushland I_{WUE} values approached the 2.5 kg m^{-3} values for WUE in the more humid sites indicating the greater effectiveness of the applied irrigation component of the total water balance. The mean ET_{WUE} from these experiments was 2.49 kg m^{-3}, which was essentially the same as the humid site WUE value of 2.5 kg m^{-3} from Tanner and Sinclair (1983). The higher ET_{WUE} values compared with the I_{WUE} values at near maximum ET or I, indicate either the lack of use of the extra water by the crop or the ineffectiveness of the rainfall combined with the irrigation. In almost every case, a slight under irrigation (about 0.75 to 0.8 of full irrigation or withholding early vegetative irrigations) maximized WUE, ET_{WUE}, and I_{WUE}. The main exception was the high ET_{WUE} and I_{WUE} values for the LEPA irrigated corn for the lower irrigation fractions. This may be attributed to the effects of the furrow dikes used with LEPA to reduce plot surface water redistribution or surface runoff despite that the drip and surface plots were leveled and bordered.

ENHANCING WATERSHED AND BASIN WUE IN IRRIGATED AGRICULTURE

On-farm irrigation technology can most certainly be enhanced as discussed in the prior section. However, these increases in WUE and reductions in water losses only have economic consequences depending on the cost of the water and if any environmental costs are assigned to the degradation or depletion of the water resource (Carter et al., 1999). The "savings" of any water will depend on whether the watershed or basin is "closed" (no usable water leaves the basin or project) or "open" (when usable water does leave the basin or project). Agriculture consumes more than 80 percent of the world's developed water supplies. Traditional gravity system efficiency maybe only 40 percent (Seckler, 1996) and uses a large fraction of the freshwater withdrawals, particularly in most western U.S. states and in many countries around the world. Any increase in use effectiveness is "perceived" to "free up" water for other users. This argument is frequently used in municipal versus agriculture battles (legal or just verbal ones). These water losses or gains (depending on your side of the argument) have been called "wet" or "real" losses or "dry" and "paper" losses (Seckler, 1996; Keller et al., 1996). Willardson et al. (1994) and Allen and Willardson (1997) favored avoiding using "irrigation efficiency" by instead defining the fraction of water that is "consumed," "unavailable to other users," and "returned to the hydrologic system for reuse." Several factors need to be considered if the water must be lifted (pumped) for reuse (as is the typical case with "tailwater" recycling schemes) and/or any operational costs for water treatment (trash removal, filtration, etc.).

When water is diverted within a watershed or hydrologic basin for irrigation, three *basic* losses can result: 1) part of the water is consumed in evaporation (from canals, from crops, etc.); 2) a portion can percolate to surface or subsurface areas (canal seepage, root zone deep percolation), with some inherently "lost" so that it cannot be recaptured (in the unsaturated vadose zone, the ocean, or a salt sink, etc.) while another part may be recaptured (interceptor drains into a drainage canal, a drainage well, etc.) where it can still be used as an additional supply; or 3) the drainage water becomes "polluted" from salts or chemicals (nutrients, pesticides, etc.) that are so concentrated that the water is no longer usable and must be discharged to a sink for disposal. In an "open" system with plentiful water, few problems exist or develop. The main problem might be capture and distribution of this water and excessive irrigations leading to waterlogging and/or salination. But as the basin approaches a "closed" state where all usable water is captured and allocated, all that remains are the consumed water and the water so polluted it cannot be used. This latter problem is very common, and pits the "head end" (close to diversion point) people against the "tail end" (low end of the system) people or "the senior right" (first priority) holders against the "junior right" (lowest priority) holders. In essence, only a change in "consumption" or in the unusable reduction to a sink, can be considered as "conserved water." In some cases, enhanced WUE results in more water consumption, and a higher irrigation efficiency can result in "less" water being available in the basin.

Examples:
Irrigation in the Texas High Plains is primarily from the Ogallala Aquifer (known as the High Plains aquifer), which is essentially a "closed" basin (minimum recharge, small stream flow exports). Many technologies have improved on-farm irrigation application efficiencies (Musick and Walker, 1987) and reduced mean annual application depths. Crop yields have increased as well (TASS, 1999) due to enhanced agronomic practices like improved varieties, fertility, pest control, etc. (see Musick et al., 1994 for winter wheat). However, WUE in this region has increased for wheat (Fig. 5; Musick et al., 1994) and corn (Fig. 6; Howell and Tolk, 1998) mainly in response to irrigation (both curvilinear due to the yield-ET offset). If the irrigated area was constant or reduced, then the "dry" water savings (those projected based on increasing irrigation efficiency or the consumed fraction) could be converted into "wet" water savings (real water conservation).

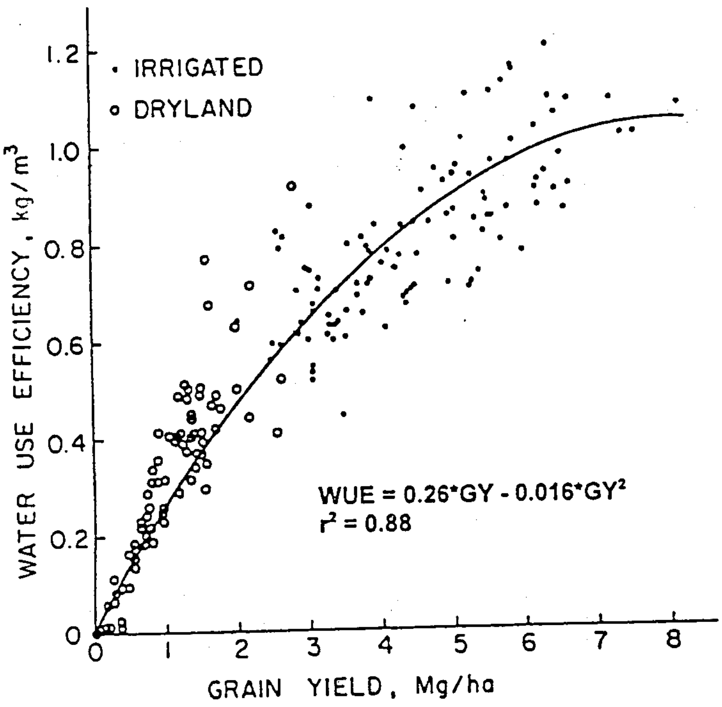

Figure 5. Relationship between winter wheat yield and water use efficiency at Bushland, TX (Musick et al., 1994).

Otherwise, the improved irrigation efficiencies simply permit irrigated land to be expanded (in a non-limited arable land situation), as is likely the case for most of the "new" irrigation in the Texas High Plains (Fig. 3). Some water districts are imposing strict regulations on new wells in this region that do effectively reduce groundwater depletion and that conserve "wet" water.

Allen and Willardson (1997) provide several interesting examples of "open" systems in eastern Idaho that traditionally have low irrigation efficiency and small actual water consumption. These irrigation projects (districts) divert considerably more water than is consumed by the crops with substantial amounts of water seeping into the groundwater and/or returning back to the Snake River for downstream diversion by other users or projects. This multiple reuse from the irrigation-induced recharge in Idaho was noted to improve river fisheries ($80 million/yr), enhance hydropower production especially during low-flow periods ($20 million/yr), reduce river flooding, and reduce pumping lifts from the aquifer. They noted the problem of reduced irrigation diversions for "junior permit" holders downstream, and the reduced "flushing" (removal of sediment buildups) of the Snake River during periods of high river flows months.

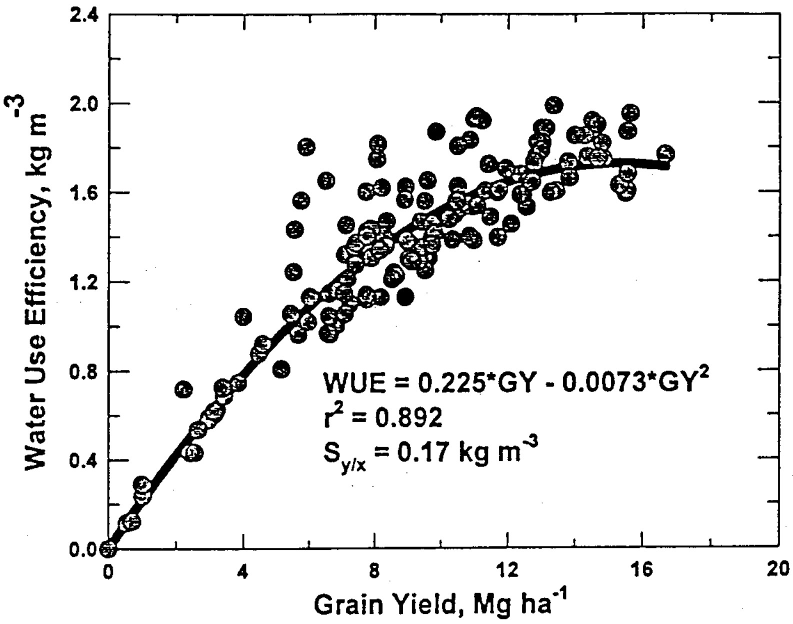

Figure 6. Relationship between WUE and grain yield for corn at Bushland, TX (Howell and Tolk, 1998).

SUMMARY

Irrigation remains vitally important worldwide and especially in the U.S. to enhance production and thereby the need to increase WUE. Many agronomic, engineering, and management technologies can reduce non-productive water use in irrigated agriculture. However, in some cases increasing irrigation efficiencies may not simply achieve "new" water for allocation unless the consumptive use part of the diverted water is actually reduced. Seckler (1996) summarized these opportunities as:

- Increasing output per unit of evapotranspiration (essentially WUE)
- Reducing losses of usable water to sinks
- Reducing water pollution (from sediments, salinity, nutrients, and other agrochemicals)
- Reallocating water from lower valued to higher valued uses

The latter opportunity can be "positive" or "negative" to agriculture depending on how secondary and tertiary interest holders are addressed.

REFERENCES

1. Allen, R.G., and L.S. Willardson. 1997. Water use definitions and their use for accessing the impacts of water conservation. Presented at the ICID Workshop

"Sustainable Irrigation in Areas of Water Scarcity and Drought," Oxford, England, Sept. 11-12.

2. Bos, M.G. 1980. Irrigation efficiencies at crop production level. ICID Bulletin 29(2):18-25, 60.

3. Bos, M.G. 1985. Summary of ICID definitions of irrigation efficiency. ICID Bulletin 34:28-31.

4. Brown, L.R. 1999. Feeding nine billion. pp. 115-132. *In* L. Starke (ed.) State of the World 1999, W.W. Norton & Co., New York, NY.

5. Burt, C. M., A.J. Clemmens, T.S. Strelkoff, K.H. Solomon, R.D. Bliesner, L. Hardy, T.A. Howell, A., and D.E. Eisenhauer. 1997. Irrigation performance measures: Efficiency and Uniformity. J. Irrig. Drainage Engr. 123(6):423-442.

6. Carter, R., M. Kay, and K. Weatherhead. 1999. Water losses on smallholder irrigation schemes. Agric. Water Manage. 40:115-24.

7. Clothier, B.E. 1983. Research imperatives for irrigation science. J. of Irrig. and Drain. Engr. (ASCE) 115(3):421-448.

8. Clothier, B.E., and S.R. Green. 1994. Rootzone processes and the efficient use of irrigation water. Agric. Water Manage. 15:1-12.

9. Cooper, P.J.M., P.J. Gregory, D. Tulley, and H,G. Harris. 1987. Improving water use efficiency of annual crops in rainfed farming systems of West Africa and North Africa. Exp. Agric. 213:113-158.

10. ERS. 1997. Agricultural resources and environmental indicators, 1996-97. Agricultural Handbook No. 712, U. S. Dept. of Agric., Economics Research Service, Washington, D.C.

11. FAO. 1988. World agriculture toward 2000: An FAO study. N. Alexandratos (ed.). Bellhaven Press, London.

12. FAOSTAT. 1999. FAOSTAT statistical database. Food and Agriculture Organization of the United Nations, Rome. [http://apps.fao.org/]

13. Gardner, W. (chair), K. Frederick, H. Adelsman, J.S. Boyer, C. Congdon, D.F. Heermann, E.T. Kanemasu, R. Lacewell, L. MacDonnell, T.K. MacVicar, S.T. Pyle, L. Snow, C. Vandemoer, J. Watson, J.L. Westcoat, Jr., H.A. Wuertz, C.H. Olsen, C. Elfring, and A.A. Hall. 1996. A new era for irrigation. National Academy Press, Washington, D.C.

14. Ghassemi, F., A.J. Jakeman, and H.A. Nix. 1995. Salinization of land and water resources, human causes, extent, management, and case studies, CAB Int.

15. Gleick, P.H. 1998. The world's water: The biennial report on freshwater resources. Island Press, Washington, D.C.

16. Gleick, P.H. (ed.). 1993. Water in crisis: A guide to the World's Fresh Water Resources. Oxford Univ. Press, New York, NY.

17. Gregory, P.J. 1990. Plant management factors affecting the water use efficiency of dryland crops. pp. 171- 175. *In* P.W. Unger, T.V. Sneed, W.R. Jordan, and R. Jensen (eds.). Challenges in Dryland Agriculture, A Global Perspective, Texas A&M University, College Station.

18. Howell, T.A., A.D. Schneider, and S.R. Evett. 1997. Subsurface and surface microirrigation of corn – Southern High Plains. Trans. ASAE 40:635-641.

19. Howell, T.A., A. Yazar, A.D. Schneider, D.A. Dusek, and K.S. Copeland. 1995. Yield and water use efficiency of corn in response to LEPA irrigation. Trans. ASAE 38: 1737-1747.

20. Howell, T.A., R.H. Cuenca, and K.H. Solomon. 1990. Crop yield response. pp. 93-122. *In* G.J. Hoffman, T.A. Howell, and K.H. Solomon (eds.) Management of Farm Irrigation Systems. ASAE Mono., Am. Soc. Agric. Engr., St. Joseph, MI.

21. Howell, T.A., and J.A. Tolk. 1998. Water use efficiency of corn in the U.S. Southern High Plains. Agron. Abst.

22. Jensen, M.E., W.R. Rangeley, and P.J. Dieleman. 1990. Irrigation trends in world agriculture. pp. 31-67. *In* B.A. Stewart and D.R. Neilsen (ed.) Irrigation of Agricultural Crops, Agron. Mono. No. 30, Am. Soc. Agron., Crop Sci. Soc. Am., and Soil Sci. Soc. Am., Madison, WI.

23. Karasov, C.G. 1982. Irrigation, efficiency in water delivery. Technology 2(2):62-74.

24. Keller, A., J. Keller, and D. Seckler. 1996. Integrated water resource systems: Theory and policy implications. IIMI Research Report No. 3, Int. Irrig. Manage. Instit., Columbo, Sri Lanka.

25. Musick, J.T., O.R. Jones, and B.A. Stewart, and D.A. Dusek. 1994. Water–yield relationships for irrigated and dryland wheat in the U.S. Southern Plains. Agron. J. 86:980-996.

26. Musick, J.T., and J.D. Walker. 1987. Irrigation practices for reduced water application – Texas High Plains. Appl. Engr. in Agric. 3:190-195.

27. Musick, J.T., and D.A. Dusek. 1980. Irrigated corn yield response to water. Trans. ASAE 23:92-908, 103.

28. NASS, 1999. U.S. Department of Agriculture, National Statistical Service. http://www.usda.gov/nass/graphics/county98/cryld.htm, Washington, D.C.

29. Pereira, L.S., J.R. Gilley, and M.E. Jensen. 1996. Research agenda on sustainability of irrigated agriculture. J. of Irrig. and Drain. Engr. (ASCE) 122(3):172-177.

30. Postel, S. 1993. Water and agriculture. Chapter 5. Pp. 56-66. *In* Gleick, P.H. (ed.). Water in crisis: A guide to the World's Fresh Water Resources. Oxford Univ. Press, New York, NY.

31. Rhoades, J.D. 1997. Sustainability of irrigation: An overview of salinity problems and control strategies. pp. 1-42. *In* CWRA 1997 Annual Conf. "Footprints of Humanity: Reflections on Fifty Years of Water Resource Developments," Lethbridge, Alberta, Canada, June 3-6, 1997.

32. Seckler, D., U. Amarasinghe, D. Molden, R. de Silva, and R. Barker. 1998. World water demand and supply, 1990 to 2025: Scenarios and issues. IIMI Research Report. No. 19, Int. Irrig. Mange. Inst., Columbo, Sri Lanka.

33. Seckler, D. 1996. The new era of water resources management from "dry" to "wet" water savings. IIMI Research Report. No. 5, Int. Irrig. Mqnge. Inst., Columbo, Sri Lanka.

34. Sinclair, T.R., C.B. Tanner, and J.M. Bennett. 1984. Water-use efficiency in crop production. Bioscience 34:36-40.

35. Tanner, C.B., and T.R. Sinclair. 1983. Efficient water use in crop production: Research or re-search? pp. 1-27. *In* H.M. Taylor, W.R. Jordan, and T.R. Sinclair (eds.) Limitations to Efficient Water Use in Crop Production, Am. Soc. Agron., Crop Sci. Soc. Am., Soil Sci. Soc. Am., Madison, WI.

36. TASS. 1999. 1998 Texas agricultural statistics. Texas Agricultural Statistical Service, U.S. Dept. of Agric. and Tex. Dept. of Agric., Austin, TX.

37. USDC. 1999. 1997 census of agriculture. U.S. Dept. of Commerce, Washington, D.C.

38. Vaux, H.J., Jr. (Chair), R.M. Adams, H.W. Ayer, J.R. Hamilton, R.E. Howitt, R. Lacewell, R. Supalla, N. Whittlesey. 1996. Future of irrigated agriculture. Task Force Report No. 127, Council Agric. Sci. and Technol., Ames, IA.

39. Viets, F.G., Jr. 1962. Fertilizers and the efficient use of water. Adv. Agron. 14:223-264.

40. Wallace, J.S., and C.H. Batchelor. 1997. Managing water resources for crop production. Phil. Trans. Roy. Soc. London B 352:937-947.

41. Wang, Z., D. Zerihum, and J. Feyen. 1996. General irrigation efficiency for field water management. Agric. Water Manage. 30:123-132.

42. Willardson, L.S., R.G.. Allen, and H.D. Frederiksen. 1994. Universal fractions for the elimination of irrigation efficiency. Paper presented at the 13th Technical Conference of USCID, Denver, CO, Oct. 19-22.

43. Worldwatch Institute. 1999. Database disk, January 1999, Washington, D.C.

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